EARTH Interactions

The Role of the North Atlantic Oscillation in Shaping Regional-Scale Peak Seasonal Precipitation across the Indian Subcontinent

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Received 18 March 2010; accepted 3 October 2010

ABSTRACT: The present study focuses on the impact of the North Atlantic Oscillation (NAO) in shaping the regional-level precipitation during the peak months of the two main rainy seasons over the Indian subcontinent. Monthly precipitation data from 1871 to 2005 were collected for 30 homogenous regions across the subcontinent. Regression analysis was used to analyze the strength of the relationship between NAO on regional-level precipitation patterns. The results of the study showed distinct spatial variations in the response of regional-level rainfall to the monthly NAO index. There were greater variations in the strength of the regression coefficients for peak monsoon rainfall (PMR) compared to the peak winter rainfall (PWR) season. During the latter half of the year, the association between PMR and the NAO index was predominantly negative. In general, the role of NAO was more pronounced across most of the regions in the peninsular India.

KEYWORDS: NAO; Monsoon; India

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DOI: 10.1175/2010EI339.1

1. Introduction

The annual variability in rainfall amounts across the Indian subcontinent, particularly during the summer monsoon season, has been widely studied over the past few decades. The amount of precipitation occurring during each year is critical for the predominantly agricultural economy in South Asia, so accurate seasonal rainfall prediction is essential. The rainfall processes occurring above the subcontinent are a result of both local and global factors. Among the global-level factors, the role of teleconnections, particularly El Niño–Southern Oscillation (ENSO) on the all Indian summer monsoon rainfall (AISMR), has been widely studied (Khandekar 1979; Pant and Parthasarathy 1981; Verma 1994; Krishnamurthy and Goswami 2000; Sen Roy et al. 2003). However, in the recent years there has been a weakening of some of the long established associations between ENSO and the Indian monsoon. Several studies have examined possible causes of this changing ENSO–AISMR relationship. One of them is the weakening relationship in the modulating effect of Atlantic Ocean circulations on the AISMR (Chang et al. 2001). Their study attributed it to the likely strengthening and poleward shift of the jet stream over the North Atlantic, resulting in a significant correlation between wintertime European surface air temperatures and subsequent monsoon rainfall in South Asia.

In this context, the role of the well-known teleconnection involving the North Atlantic Oscillation (NAO) on AISMR is particularly relevant. NAO is generally defined as the dominant mode of variability in the Atlantic Ocean, and it accounts for more than 36% of the variance in mean sea level pressure during winter months (Walker and Bliss 1932). It is mainly associated with variations in surface westerlies crossing the North Atlantic Ocean aimed at Europe. It has been observed during high NAO winters that the westerlies above Europe are slightly stronger than in low NAO winters (Hurrell 1995). As a result, studies have shown a significant impact of NAO on winter weather, in both North America and Europe, in the form of changes in winter storm tracks (Rodwell et al. 1999; Trigo et al. 2002). Unlike some of the other well-known teleconnections such as ENSO, no clear periodicity has been identified in the case of NAO. However, there have been several periods of high and low NAO index values: a downward trend in NAO values from the early 1940s to the 1970s, followed by strong values over the next 25 years (Hurrell 1995).

There are a limited number of studies exploring the role of NAO on AISMR. One of the earliest studies was by Dugam et al. (Dugam et al. 1997), who investigated the role of NAO on AISMR, as well as two major subdivisions of the subcontinent including northwestern and peninsular India. The results of this analysis showed that the NAO index prevailing during the spring and winter months revealed a statistically inverse relationship with respect to monsoon rainfall. In another study, Kakade and Dugam (Kakade and Dugam 2000) found an overall negative correlation between the NAO index in April and AISMR. There is also evidence of a combined effect of NAO and the much-analyzed Southern Oscillation (SO) on the AISMR (Kakade and Dugam 2006). The AISMR is not only influenced by interannual variations in the atmospheric circulations prevailing over the North Atlantic Ocean, but it is also impacted by variations in sea surface temperatures (SSTs) in the North Atlantic (Goswami et al. 2006). Specifically, it was mentioned that, on interannual time scales, strong NAO index values influenced the monsoon by altering tropospheric temperature anomalies over Eurasia.

However, none of these studies examine the spatial variations, if any, in the impact of NAO on monsoonal rainfall across the Indian subcontinent. An extensive review of literature reveals one such study, which consisted of a correlation analysis regarding the effect of NAO on two broad regions of the Indian subcontinent by Dugam et al. (Dugam et al. 1997). The results indicated substantial variations between those two regions between 1881 and 1988, which indicates that a more detailed regional-level study is needed to reveal regional-level differences in the NAO–monsoon rainfall relationship. Furthermore, there is evidence of monsoon forecast failure in recent years, which requires the need of updating these results with newer data. For instance, in 1997, one of the strongest El Niño years of the twentieth century, the forecast for monsoon rainfall was below normal; nevertheless, it turned out to be a normal monsoon rainfall year. Finally, there are no studies that examine the influence of NAO on winter rainfall, which is particularly important because of the strengthening of NAO during winter months, except in the case of the northwestern Himalayas. In a recently published study, Bhutiyani et al. (Bhutiyani et al. 2009) found a statistically significant relationship between winter rainfall and the NAO index, which validated the findings of previous studies (Archer and Fowler 2004; Fowler and Archer 2005; Fowler and Archer 2006). This study seeks to fill that gap and highlight the role of NAO on shaping seasonal rainfall at the regional scale in the Indian subcontinent.

2. Data sources

Monthly precipitation data from 1871 to 2005 for 30 homogenous rainfall regions distributed across the Indian subcontinent were collected for this study (Figure 1). The monthly precipitation dataset was developed by the Indian Institute of Tropical Meteorology (IITM), using precipitation data from an evenly distributed network of 306 precipitation-gauge stations. This station network provided adequate representation for each district that demarcates an administrative unit in India. Next, the monthly area-weighted precipitation for each meteorological subdivision demarcated by the India Meteorological Department (IMD) was calculated by assigning the district area to its representative station. Thus, meteorological subdivisions are regional-level units, which retain the regional climate characteristics while removing the noise of highly localized climatic influences in the data (Pant and Rupa Kumar 1997). Additional details on the methodology used in compiling this dataset are available in Parthasarathy et al. (Parthasarathy et al. 1995). The entire subcontinent was completely covered, except for the highland regions in the far north and northeast, for which there were inadequate data availability. There were no missing data in the entire dataset. This dataset has been widely used in several recent studies that analyze precipitation patterns across the Indian subcontinent (Kakade and Dugam 2000; Naidu et al. 2009).

The NAO is usually defined as the normalized pressure differences between the Azores and Iceland (Walker and Bliss 1932). Data on the NAO index from 1871 to 2000 were downloaded from the Climate Research Unit Web site (available online at http://www.cru.uea.ac.uk/cru/data/nao/). This dataset was developed by employing station-level data from Reykjavik (Iceland), Gibraltar, and Ponta Delgada

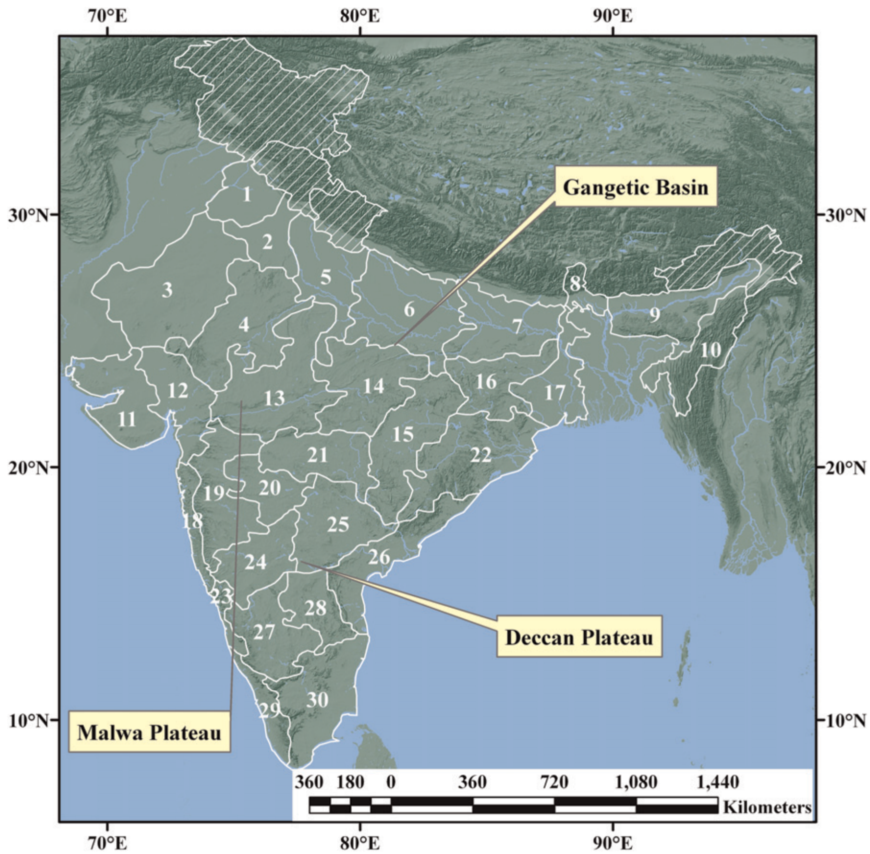

Figure 1. Homogenous rainfall regions across the Indian subcontinent: 1) Punjab; 2) Haryana; 3) western Rajasthan; 4) eastern Rajasthan; 5) western Uttar Pradesh; 6) eastern Uttar Pradesh; 7) Bihar; 8) sub-Himalayan West Bengal; 9) Assam and Meghalaya; 10) Nagaland, Manipur, Mizoram, and Tripura; 11) Saurashtra and Kutchh; 12) Gujarat; 13) western Madhya Pradesh; 14) eastern Madhya Pradesh; 15) Chhattisgarh; 16) Jharkhand; 17) Gangetic West Bengal; 18) Konkan and Goa; 19) Madhya Maharashtra; 20) Marathwada; 21) Vidarbha; 22) Orissa; 23) coastal Karnataka; 24) North Interior Karnataka; 25) Telengana; 26) coastal Andhra Pradesh; 27) South Interior Karnataka; 28) Rayalseema; 29) Kerala; 30) Tamil Nadu. Hatched regions include the hilly regions for which no data were available.

(Azores), and a detailed description is available in Jones et al. (Jones et al. 1997). The NAO index data from 2000 to 2005 were obtained from the Climate Prediction Center Web site (available online at http://www.cru.uea.ac.uk/~timo/datapages/naoi.htm).

3. Analysis and results

Given the objective of the study to examine the influence of NAO on the subcontinent's two main wet seasons (summer monsoon and winter rainy season), the following two sections include the results for each season separately.

3.1. Spatial variations in the role of NAO on resulting regional-scale PMR

Monsoon phenomena over the subcontinent are characterized by the seasonal reversal of winds. This seasonal reversal of winds is mainly triggered by the differential heating of the Indian landmass relative to adjacent water bodies, which creates onshore winds during the monsoon months. According to the IMD classification, the monsoon season extends from June to September. Typically, the first monsoon showers hit the southwest coast of India in Kerala around the first week of June. Over the following month, the rains expand across the entire subcontinent, with an approximate onset date of 1 July in Delhi located in northwestern India. Similarly, by the beginning of September the monsoon circulation starts withdrawing from northwestern India. As a result, the months of July and August are considered as the peak monsoon rainfall (PMR) months because the entire subcontinent is firmly under monsoon circulation.

Even though NAO is more dominant during the winter months of December–February, it has been shown that the oscillation can be present throughout the year (Barnston and Livezey 1987). Here, the individual month-to-month effect of NAO on peak summer monsoon rainfall has been examined to determine which part of the year has the maximum influence on the different regions. Linear regression was performed with average peak monthly monsoon data as the dependent variable and monthly NAO index values as the independent variable. The results of these analyses, in the form of Pearson correlation coefficients, were mapped to determine the spatial patterns in the regional-scale responses of PMR to the monthly NAO index (Figure 2).

The response to January NAO index values was predominantly negative for most of the subcontinent (Figure 2a). A few of the regions showed a negative association, located mainly in the northwest (Gujarat, eastern Rajasthan, and Uttarakhand), in the east (Bihar and Jharkhand), and central peninsular India (Telengana and Rayalseema). During February, negative associations at the regional scale were stronger (Figure 2b). The highest positive coefficients were observed in the north for the Gangetic basin and parts of western Rajasthan in the northwest, as well as in south-central India in Rayalseema and interior Karnataka (Figure 2b). Neutral to weak positive associations (less than 0.05) were observed for isolated regions in the southwest (Kerala, Konkan, and Goa), Gujarat, and in the eastern Gangetic basin (Jharkhand and Bengal).

A distinct change in the influence of NAO on PMR for March is observed, with most of the subcontinent showing a positive association (Figure 2c). The strongest positive coefficients (around 0.2) were observed for northwestern India (western Rajasthan and Gujarat) and Telengana in south-central India, which were also statistically significant at the 0.10 confidence level. However, moderately strong negative coefficients were observed for two clusters: one in the northern part of the Gangetic basin (eastern Madhya Pradesh, eastern Uttar Pradesh, Bihar, Bengal, and northeast India), and the second located in Tamil Nadu in the far southeast. For March and April, there was general progression of the negative response of PMR to the NAO index from the east to west (Figure 2d). However, the overall relationship was mostly neutral to weak across most of the subcontinent. Relatively stronger negative coefficients were observed over northern India (Punjab and Haryana) and

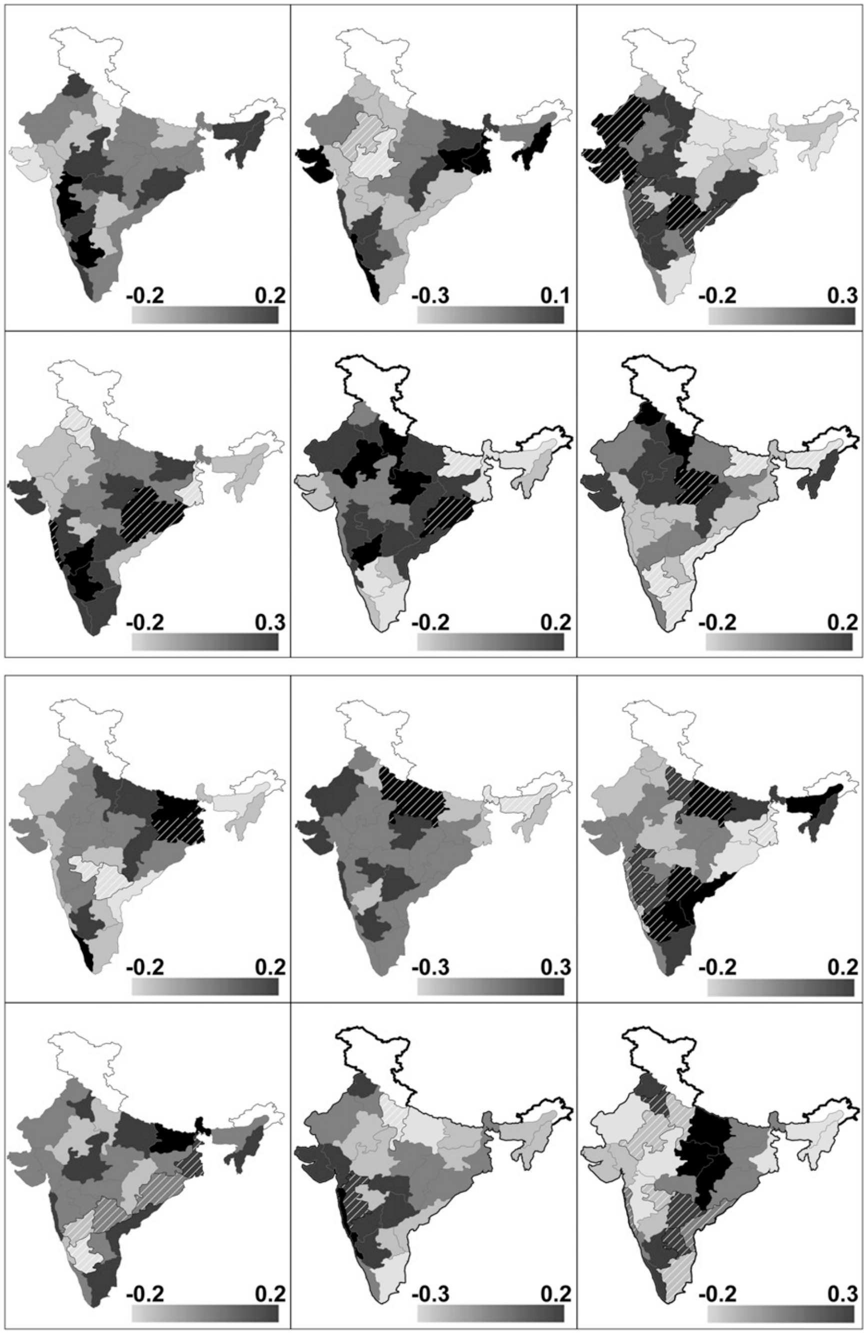

Figure 2. Influence of NAO on average PMR in the form of Pearson correlation coefficients: (a) January, (b) February, (c) March, (d) April, (e) May, (f) June, (g) July, (h) August, (i) September, (j) October, (k) November, and (l) December NAO indexes. White slanted hatches on the different regions are for areas that showed a statistically significant relationship with NAO at greater than 90% significant level.

Bengal in eastern the Gangetic basin, whereas relatively stronger positive values were observed in central India (Orissa and eastern Madhya Pradesh), Karnataka, and the western coastal strip. During May, most of the core of the subcontinent showed a relatively weak positive association, except for the outer regions located near the southern end of the peninsula, Gujarat in the west, and the eastern Gangetic basin extending into the northeast India (Figure 2e).

For June, there was a complete reversal of the relationship between NAO and PMR, with most of the continent exhibiting a negative relationship (Figure 2f). The strongest negative coefficients were observed for the southeastern and northeastern subdivisions, which were also statistically significant at the 0.10 confidence level. On the other hand, positive coefficients were mainly concentrated in the core of the subcontinent extending in northwesterly direction and included Punjab and Haryana subdivisions. The positive association with NAO extended eastward during July to cover the entire Gangetic basin and parts of Malwa Plateau in central India (Figure 2g). Positive coefficients were also observed over southwest India in Kerala and southern Karnataka as well as Gujarat in the west. The rest of the subcontinent showed a negative correlation with NAO, with the strongest values (close to -0.2) concentrated over southeastern India (Telengana, coastal Andhra Pradesh, and Tamil Nadu). The northeastern subdivisions also experienced moderately strong negative coefficients. For August, the relationships were mostly positive across the subcontinent (Figure 2h). The strongest positive coefficients were located in the central Gangetic basin, extending northward to the foothills of the Himalaya and northwestern India. The negative coefficients were located in northeastern India.

For the months of September–December, the analyses were conducted for the lag year (the relationship between average PMR activity and the NAO index measured in the preceding year for those specific months). The NAO–PMR association during September mostly matched the patterns from the preceding month of August, with most of the continent showing neutral to a moderately positive response to the NAO index (Figure 2i). The strongest positive coefficients (around 0.2) were observed for south-central India in coastal Andhra Pradesh, Rayalseema, Telengana, and interior Karnataka, as well as in the northwest. The negative coefficients extended in an east–west direction from Rajasthan in the northwest to Orissa on the northeast coast. The regions along the foothills of the Himalaya in the Gangetic basin also showed a positive correlation with the NAO index. During October, the coefficients were mainly neutral to negative for most of the subcontinent (Figure 2j). Positive coefficients were scattered along the foothills of the Himalaya in the northern Gangetic basin, including eastern Uttar Pradesh, Bihar, and Bengal, as well as western Madhya Pradesh, Konkan, and Goa on the west coast and Tamil Nadu in the far southeast. November showed distinct regionalization in the patterns of the coefficients (Figure 2k). All of western India extending southward from Gujarat to Kerala in the south, including most of Madhya Pradesh and Chhattisgarh in the center, showed a positive response. The negative coefficients extended from northwestern India eastward to include the Gangetic basin and Orissa on the northeast coast. Finally, in December the observed coefficients were mainly positive, with relatively stronger values (around 0.2) concentrated over the Gangetic basin in eastern Uttar Pradesh, eastern Madhya Pradesh, and Chhattisgarh (Figure 2l). Negative relationships between NAO index and PMR

Table 1. List of El Niño and La Niña years taken into consideration during the study period.

El Niño years	1951, 1953, 1957–58, 1963–64, 1965–66, 1968–70, 1972–73, 1976–77, 1977–78, 1982–83, 1986–88, 1990–92, 1993, 1994–95, 1997–98
La Niña years	1950–51, 1954–56, 1964–65, 1967–68, 1970–72, 1973–76, 1984–85, 1988–89, 1995–96, 1998–2000, 2000–01

were located in the northeast regions and Bengal in the eastern section of the subcontinent, western Rajasthan, and northern parts of the Deccan Plateau including parts of Madhya Pradesh and Maharashtra. It is noteworthy that NAO is more dominant during the winter months, specifically during December. Furthermore, the observed correlation coefficients for most of the regions in peninsular India were statistically significant at the 0.10 confidence level. It has been mentioned by Gutzler and Rosen (Gutzler and Rosen 1992) that, during the negative phase of NAO, there is a poleward shift of the Icelandic low and Azores high, which leads to a decline in Eurasian snow cover. This results in a more pronounced ocean–land contrast, which leads to an earlier and stronger Asian monsoon (Walker 1910; Hahn and Shukla 1976; Kakade and Dugam 2000).

The relationship between NAO and PMR amounts were also analyzed for El Niño and La Niña years. The results indicated greater strength in the NAO–PMR relationship over majority of the regions for certain months during El Niño years, specifically during March and April as well as from August to October (Table 1). It is also important to note that only 8 out of the 30 homogenous regions studied showed a weaker role of NAO during El Niño years for less than six months of the year. These regions were mainly concentrated in the northeast extending southward toward Orissa and also in Karnataka in the south.

3.2. Spatial variations in the role of NAO on resulting regional-scale PWR

The majority of studies on the variability of precipitation processes focus on summer monsoon precipitation. Even though most of the precipitation occurring over the subcontinent takes place during the monsoon season, substantial precipitation occurs during the winter months of January and February. This is relevant to the present study because NAO is strongest during the winter months. The atmospheric processes associated with the subcontinent's winter rainfall are dominated by the relative location of the ascending arm of the Hadley cell above the adjacent Indian Ocean near Malaysia and Indonesia (Das 1986). Winter precipitation over the subcontinent is a result of the movement of western disturbances in the form of low pressure systems, especially in northwestern India.

The results of the regression analysis of the impact of NAO on peak winter rainfall (PWR), which includes the months of January and February, are shown in Figure 3. These analyses were conducted by using the average winter precipitation each year as the dependent variable and the monthly NAO index as independent variables. Similar to the summer monsoon precipitation analyses, the winter precipitation analyses used concurrent years for the two winter months and for the rest of the year there was a 1-yr lag. There were substantial variations at the regional

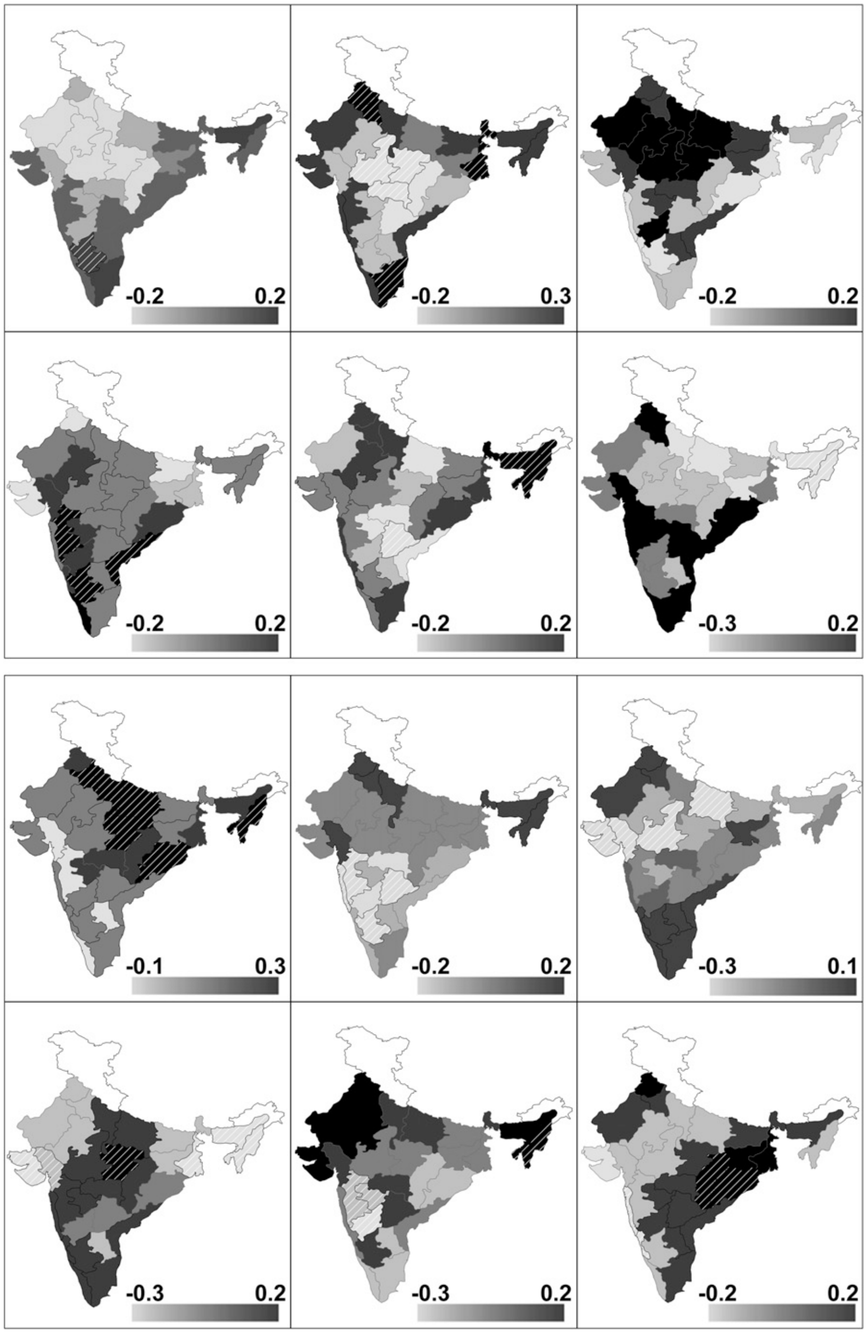

Figure 3. As in Figure 2, but for the average peak winter rainfall (PWR).

scale for the different months. During January, the observed coefficients were mostly negative for the interior of the subcontinent, with the strongest negative coefficients concentrated in the arid region of Rajasthan and Madhya Pradesh (Figure 3a). Positive coefficients (around 0.2) were observed in the peninsular region and in the northeast, which also received a comparatively greater amount of rainfall in winter. A southward progression of the negative relationship between NAO and PWR is observed during the subsequent month of February (Figure 3b). Interestingly, there is an overall relative weakening of the negative coefficients. For instance, in the case of Chhattisgarh the coefficient decreased from −0.10 in February to −0.02 in March, and in Telengana it decreased from −0.10 in February to −0.03 in March. This is even more evident for the next three months, when most of the regional-scale precipitation totals show a positive response to the NAO index, as seen in the case of Chhattisgarh (from −0.01 in February to 0.07 in April and 0.03 in May), eastern Madhya Pradesh (−0.16 in February to 0.06 in March), Marathwada (from −0.09 in February to 0.08 in March), northern interior Karnataka (−0.03 in February to 0.1 in April), and southern interior Karnataka (−0.06 in February to 0.2 in April). The coefficients observed in the central core of the Indian subcontinent were also statistically significant.

In general, the range in the strength of the coefficients did not change during the different months, remaining between −0.2 and 0.2. However, there are substantial spatial variations in the positive coefficients. For instance, in March the entire Gangetic basin showed a relatively strong positive response to the prevailing NAO index (Figure 3c). The areas of negative response were mostly concentrated in the southern peninsula and in the northeast. Incidentally, the regional-level response of PWR patterns during March is almost a complete reversal of what was observed for the month of January. During April, most of the regions in the subcontinent experienced a positive response to the NAO index, except Gujarat and Haryana in the west and Bihar, Chhattisgarh, and Bengal in the east (Figure 3d). The strongest positive coefficients (around 0.2) were concentrated in the western peninsula in Kerala and interior Karnataka, which were also statistically significant at the 0.10 confidence level. The predominantly positive response of regional-scale PWR to the NAO index continued to prevail during May for most of subcontinent (Figure 3e). However, there was an increase in the area of negative response to NAO index extending southward from eastern Uttar Pradesh to Andhra Pradesh in the south. Over the next few months, excluding July, there is a general spread in the negative response of regional-scale PWR to the NAO index. During June, the Gangetic Plain extending into the foothills of the Himalaya showed a negative response (Figure 3f). The remaining regions mostly showed a weak positive association with the June NAO index. As mentioned above, the spatial patterns were mostly positive during July with the relatively stronger positive coefficients (greater than 0.2) observed over Punjab, Haryana, and parts of Uttar Pradesh (Figure 3g). However, the spatial patterns were completely reversed during August, with most of the regions exhibiting a negative response to NAO (Figure 3h). Regional concentrations were limited to small areas of positive coefficients in the northwest and northeast. Overall, the regional-scale PWR showed the widest geographic spread in negative association with the August NAO index, with a majority of the regions in peninsular India exhibiting a statistically significant negative relationship.

During September, the spatial spread of negative coefficients contracted to mainly the central section of the subcontinent, excluding the northwestern regions and the peninsular regions in the far south (Figure 3i). However, there was a slight increase in the strength of the observed negative coefficients, particularly in western India in Gujarat and Madhya Pradesh. In October, most of the central part of subcontinent extending from Uttar Pradesh in the north all the way to Tamil Nadu and

Kerala indicated relatively weak positive associations with the prevailing NAO index (Figure 3j). Nonetheless, relatively stronger negative coefficients (greater than -0.2) were observed in the west (Rajasthan and Gujarat) and in the east (from Bihar to northeastern India). The negative association with the winter NAO index expanded during November over most of the subcontinent, with patterns almost reversed from the previous month (Figure 3k). The overall strength of the negative coefficients was also comparatively weaker for most of the regions across the subcontinent. Finally, during December the negative association between NAO index and regional PWR were visible mostly in western parts of the subcontinent, whereas the eastern half of the subcontinent showed a positive association (Figure 3l).

4. Conclusions

From this discussion, it is evident that NAO plays a role in shaping the regional-scale spatial patterns of precipitation in the Indian subcontinent. Although the general effects of NAO on AISMR is known, this study has explored the regional-scale variations of the monthly NAO index on peak season rainfall occurring during both summer and winter months. Peak season rainfall during the summer monsoon months included July and August, whereas the peak winter months are January and February. The month-to-month role of the NAO index on peak seasonal rainfall was analyzed from 1871 to 2002. The main findings of the study can be summarized as follows:

- The role of NAO on PMR varied at the monthly scale, with relatively stronger positive coefficients observed during August and September. Slightly stronger negative coefficients were observed during February.
- During a majority of months, the relationship between PMR and NAO was positive over the eastern part of the Gangetic basin.
- Because NAO is more pronounced during the winter months, the observed coefficients during those months were mostly negative over the peninsular India in case of the PMR.
- The negative response of PWR to the NAO index during a majority of months was concentrated in the northern part of the subcontinent, ranging from the arid regions of northwestern India to the wetter regions in the east.
- The role of the NAO index was predominantly negative across most of the subcontinent during August and November, whereas the reverse was observed during April and July when the coefficients were positive across most of the regions for PWR.
- Given the pronounced role of ENSO on Indian precipitation, analyses of NAO influences were also conducted during El Niño and La Niña years. Results showed no significant differences between the different sets of years. This is important in view of the changing role of ENSO on Indian monsoon precipitation patterns.

This study has explored the relationship between the monthly NAO index and regional-scale peak seasonal precipitation patterns in the Indian subcontinent. Its results will assist in constructing more robust seasonal forecasts, which is particularly important for South Asia's massive agricultural sector. Even though NAO does not explain significant levels of variation in the peak seasonal precipitation occurring over the subcontinent, these results reveal the overall role of NAO on precipitation patterns.

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